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EXECUTIVE SUMMARY

METALLURGICAL EXAMINATION OF OVERHEATED WATERWALL TUBES - NANTICOKE GS, UNIT 1

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Inspection by station personnel of an area with a history of overheating-related tube failures revealed bulging in certain tubes; these were removed and forwarded to Research for examination. Particular interest was expressed in distinguishing between long term moderate or short term severe overheating.

Diametral measurements were made which showed that creep strain was general as well as concentrated in bulges. Microstructural examination showed that the creep was due to long term moderate overheating and the effective operating temperature over the life of the unit was determined to have been ~450°C. The overheating was confined to a narrow band on the crown of the tubes and was presumed to have resulted from a well-defined pattern of steam blanketing. It was not possible to determine whether the overheating was due to excess heat flux, restricted internal flow, or a combination of factors. Recommendation was made to use available technology for measuring the above operational parameters.

job	file	date	report no.
740684-265-572	827.51	November 19, 1984	84-366-K

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To Mr. T.J. Popiel
Thermal Generation Division

METALLURGICAL EXAMINATION OF OVERHEATED WATERWALL TUBES - NANTICOKE GS, UNIT 1

H.J. Westwood

Diametral measurements have been made to quantify creep strains and local bulges resulting from overtemperature exposure of tubes taken from a boiler region with an overheating history. Microstructural examination has shown that the observed swelling was due to long term moderate rather than short term severe overheating. The effective operating temperature over the life of the unit was estimated as ~450°C. The overheating was confined to a narrow band on the crown of the tubes and was presumed to have resulted from a well-defined pattern of steam blanketing. It was not possible to determine whether the overheating was due to excess heat flux, restricted internal circulation, or a combination of factors.

INTRODUCTION

During a recent inspection of Unit 1 waterwall tubing in an area with a history of overheating-promoted failures, several tubes were found to have slight bulges and "alligator hide" typical of creep strain caused by overtemperature operation. The tubes were removed and forwarded to Research to be examined from metallurgical and corrosion aspects; particular interest lay in differentiating, if possible, between short term severe or long term moderate overheating and in identifying the problem as fireside or waterside-initiated. Tube locations were numbers 7 and 8 from the south waterwall on the west wall between elevations 640 and 650 feet; this is the windbox region so that the tubes were not insulated on the cold side. Tube 23 from the north corner was also received; it had been

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removed because of unusually adherent fireside scale. Tubes were internally rifled, had a nominal OD of 63.5 mm and were fabricated from A210 Grade A1 medium carbon steel.

This report concerns metallurgical examination of tubes 7 and 8; the corrosion investigation on these tubes and also tube 23 is being reported separately.

METALLURGICAL INVESTIGATION

The membrane-welded tubes 7 and 8 were received as three separate sections designated Top, Middle Bottom; these were thought to be from a continuous length but, during the course of the work, it became apparent that some tubing was missing between the top and middle sections.

The tubes were inspected visually, diametral measurements were made and metallographic examination of selected locations was carried out.

(i) Visual Inspection

Visual inspection, tactile examination and straightedge application confirmed that bulges were present in the tubes. Associated with the bulges but also present, though less pronounced, in other areas was predominantly longitudinal surface cracking, usually described as alligator-hide; a typical example is shown in Figure 1 from tube 7.

The ID surface showed a band of unusually thick magnetite, in some cases exfoliated, running down the crown of the hot side of the tube and being about 30 mm in width. Figures 2(a) and 2(b) show hot and cold side ID surfaces. In some of the hot side regions, oxidation had been heavy enough almost to remove the rifling.

(ii) Diametral Measurements

To quantify the obvious creep strains in the tubes, precise diametral measurements were made normal to the membrane plane using a vernier caliper capable of reading to 0.02 mm. Since it was not possible to clean the tube surfaces (because of subsequent corrosion investigations), it was not realistic to report dimensions to such a degree of accuracy; readings are accordingly given to an accuracy of 0.1 mm.

Results for the three sections of tubes 7 and 8 are presented in Figures 3, 4 and 5. Clearly, some scatter is evident, undoubtedly due to local surface irregularities. It is obvious, however, that bulges are present in both tubes, those in tube 7 being particularly pronounced. Less obvious, but also important is that significant strain was present in almost the whole length of each tube; minimum diameters of ~63.5 mm were found at the top end of both tubes and at the bottom end of tube 8.

Even allowing for some scatter in the measured diameters, it is apparent that a significant discrepancy exists between the top and middle sections of tube 8. For this reason, it was concluded that an intermediate section of tubing had been removed at the station.

(iii) Metallographic Examination

Metallographic work concentrated on comparing microstructures in and around a bulged region with those in the least damaged area. The largest bulge was examined, ie, at the 45 cm point in the bottom section of tube 7 (See Figure 5).

Note that strain values of 9%, 6% and 3% have been assigned to points on this bulge and also a strain of 0.25% on Figure 4. These values were calculated assuming that all the overheating strain was confined to the hot side of the tube and were obtained from the equation

$$\% \text{ strain} = \frac{d - do}{do} \times 200$$

where d was the measured diameter and do the minimum diameter, taken as 63.5 mm.

All micrographs are from transverse sections and, except for Figure 6, are at a magnification of 1000X; this magnification was chosen to facilitate comparison with reference micrographs produced in earlier work on overheated carbon steel/1/.

Figure 6 shows an OD section through the alligator-hide at the maximum bulge location. Oxide penetration of surface grain boundaries is apparent and some sub-surface grain boundary cavitation is also present. The microstructure, even at this moderate magnification is clearly degenerated and will be considered later in more detail.

Assessment of microstructural change requires a basis for comparison in terms of initial conditions. In the present case, the structure farthest from the damaged region of tube 7 was used for this basis. Figure 7 shows the cold side microstructure from the 0-10 cm region of the top section. Generally, the pearlite colonies are sharply delineated; within the colonies, the carbide varies from coarse lamellar or granular to irresolvable.

The structure at the most strained (9%), part of the bulge is shown in Figure 8 and presents a drastic contrast to the reference structure in Figure 7. Pearlite colonies have essentially disappeared, carbides have spheroidized and also agglomerated.

Figure 9 shows the structure on the same (9%) section, also on the hot side of the tube but ~10 cm from the crown (Figure 8). The degree of structural degeneration is markedly lower than in Figure 8, despite the close proximity.

The structure on the cold side of the same (9%) section is shown in Figure 10; some degeneration is evident, comparable in extent to that in Figure 9.

Sections at less strained parts of the same bulge are shown in Figures 11 and 12, the strains being 6% and 3% respectively. Comparing these structures with that of the 9% strain section (Figure 8), the degree of microstructural degeneration shows an obvious correlation with strain.

Finally, the structure away from a bulge but where strain was still significant is shown in Figure 13; this section, taken at the 56 cm position on the middle section of Tube 7 had a strain of 0.25%. Some degeneration is evident, following the trend of Figures 8, 11 and 12.

DISCUSSION

It was known from the outset that these tubes had experienced excess temperatures so that the main objective of the investigation was to define the overheating as short term severe or long term moderate; in principle, either could cause the creep swelling observed.

The surface damage observed in the 9% bulged section (Figure 6) was significant in terms of temperature exposure. Intergranular cavitation, as present in association with or adjacent to the surface oxide intrusion, is essentially a medium to long term creep damage process which leads ultimately to thick-edged, macroscopically brittle fracture; such creep fractures are often encountered in superheater and reheater tubes. In waterwall tubes, so-called creep failures usually result from a severe overtemperature excursion whereby tube metal temperature reaches 850-900°C; at these temperatures and stresses, highly ductile (thin-edged) failure ensues in a matter of minutes/1,2/. Long term thick-edged fractures, though uncommon, have, however, also been observed in waterwall tubing and been associated with more moderate overheating/2/.

The degree of microstructural degradation observed in the 9% strain section could only have been caused by long term exposure to temperatures below the eutectoid transformation (~725°C); whilst a spheroidized structure could result from a single brief excursion to higher temperatures/2/, the carbide agglomeration exhibited would not occur under such conditions.

Perhaps the most striking microstructural observation was the localization of the degeneration. As shown in Figure 9, the structure about 10 cm from the crown of the 9% strained area was only slightly broken down, in fact, to essentially the same degree as on the cold side at the same location (Figure 10). This indicates that the overheating was concentrated in a narrow band, which is in good agreement with the observation of the excessive zone of scaling on the internal surface (Figure 2a).

The diametral measurements showed that creep strain was general along the tubes as well as localized (in bulges). The bulging may have been promoted by slightly higher local temperature or may simply have resulted from plastic instability.

The strains were calculated based on an implicit assumption of uniform creep deformation on the hot side only of the tube. Since the overheating was later shown to be much more localized, these strains clearly are unrealistically low. Thus, if the 9% value is re-calculated assuming the strain to be concentrated in about a 30° arc of the tube surface, a factor of ~3 should be placed on the quoted strain values. The wall thinning measured on the minimum bulged section was around 35% - some would have been due to waterside corrosion, some to creep strain. The re-calculated swelling strain of ~27% is in fair agreement with this.

Data on long term creep rupture ductility of carbon steel are sparse but a figure in the range 40-50% would probably be appropriate. It is worth noting, however, that cavitation damage, as shown in Figure 6, has rarely been observed in tubes except adjacent to an actual failure. Furthermore, recent work on creep deformation in cylindrical components has shown that accelerating creep occurs at quite small strains (≈2%). Although rupture strains of more than 30% may be observed, the large remaining deformation may occur in a very small fraction of the overall creep life/3/. The implication is that the "9%" bulge and, indeed, the smaller ones, were probably very close to final rupture.

In principle, both the microstructural degeneration and the creep deformation can be used to estimate the effective operating temperature of the tube, given the number of operating hours. Figure 14 shows the time-temperature relationship for spherodization of carbon steel in three initial conditions/4/. The A210 tube steel would probably best be considered as lying between the annealed and normalized bands in this figure. Taking an operating period of ~50 000 h, this predicts a temperature of approximately 550°C.

Considering the creep aspects, the mean diameter hoop stress on the tube was 72.9 MPa (10 575 psi) and, as discussed, it can be assumed that rupture occurred in ~50 000 h. Figure 15 shows some relevant creep data/5/ from which it appears that rupture in 50 000 h at the above stress would be predicted at a temperature of ~850°F or 455°C. Conversely, at 500°C (1022°F), rupture would be expected in less than 1000 h. Thus, a large discrepancy exists between metal temperature predicted using the two approaches.

Degree of spheroidization is somewhat subjective so that large error bands should be assumed in considering Figure 13. More importantly, however, is the effect of creep strain on microstructural breakdown. Figures 11-13 showed marked differences in degree of degeneration as a function of strain. Whilst some temperature difference may also have been involved, it is believed that strain was the main factor promoting the extreme microstructural change in the most bulged regions. This is substantiated by earlier work on overtemperature excursion effects on A210 carbon steel which showed a strong strain dependence at constant temperature/1/. The spheroidization data in Figure 14 would probably not have been obtained from strained specimens. Thus, the implication is that the degree of spheroidization which the present tubes would have exhibited in the absence of creep strain would have been substantially less; this would then reduce the predicted temperature to a level more in agreement with that predicted, more reliably, from creep considerations. It is thus concluded that the effective operating temperature was around 455°C.

The effective operating temperature is actually that temperature which, if applied continuously throughout the operating life, would have caused the observed effects. In reality, the tube temperature probably increased through the overheating period as internal scale increasingly restricted heat flux, so that recent temperatures were probably well above the 455°C value derived above. An implicit assumption in the above temperature derivation was that the overtemperature condition had existed throughout the operating life of the unit - taken as 50 000 h. In fact, the condition could have developed more recently, in which case a higher metal temperature could have existed. Without means of determining this, it is felt appropriate to specify the "effective temperature over the operating life".

It appears that the overheating resulted in well-defined steam blanketing in the crown region of the tubes, as shown by the internal scaling and localized microstructural degeneration. Steam blanketing is the consequence of the DNB phenomenon (departure from nucleate boiling) which results when the balance between heat flux and internal flow is upset. In high pressure

boilers (>2000 psi - 13.8 MPa) relying on natural circulation, the balance, particularly in high heat flux areas, is quite delicate - the deployment of rifled tubing attests to this.

In general, DNB can be due to excess heat flux, say due to flame impingement, to internal flow restriction, or to a combination of both. Complete flow blockage, often encountered after maintenance outages, causes the classic short term cod-mouth type rupture; this is clearly not the situation here. If the problem is flow-related, it may perhaps be due to uneven distribution from the lower waterwall headers. Within the scope of the present investigation, it is not possible to elucidate these aspects.

CONCLUSION

1. The tubes have been subjected to long term overheating, the effective operating temperature over the life of the unit being approximately 450°C.

2. The overheating was concentrated in a fairly narrow band on the hot side of the tubes, indicative of a well-defined pattern of steam blanketing.

3. General creep strain was present and the locally bulged areas had probably come close to final rupture.

4. It was not possible to determine whether the overheating was due to excessive heat flux, restricted internal flow or a combination of factors.

RECOMMENDATION

1. Technology is available for measuring heat flux and internal flow/6/. Depending on resource availability and cost benefit considerations, it may be considered worthwhile to characterize these operating parameters to determine the reason for tube overheating in this region of the boiler.

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2. "Analysis and Prevention of Boiler Tube Failures", CEA Report on Contract 83/237G-31, p 4-29 - 4-34, R.B. Dooley and H.J. Westwood.

3. Prediction of the Service Performance of Boiler Components Operating under Creep Conditions. J.D. Parker, D. Sidey and R.B. Dooley, Presented at Joint Power Generation Conference, October 1984, Toronto.

4. "Properties of Metals at Elevated Temperatures" by G.V. Smith, pub McGraw-Hill, p 326.

5. "Elevated Temperature Properties of Carbon Steels", ASTM STP No 180, p 44.

6. "Steam - Its Generation and Use", Babcock and Wilcox, p 33-13 to 33-25.

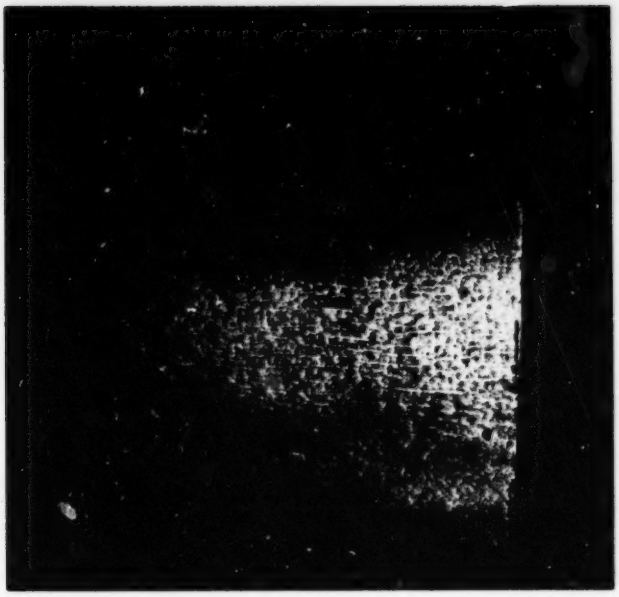


FIGURE 1 - BULGED SECTION SHOWING "ALLIGATOR-HIDE" SURFACE CRACKING.

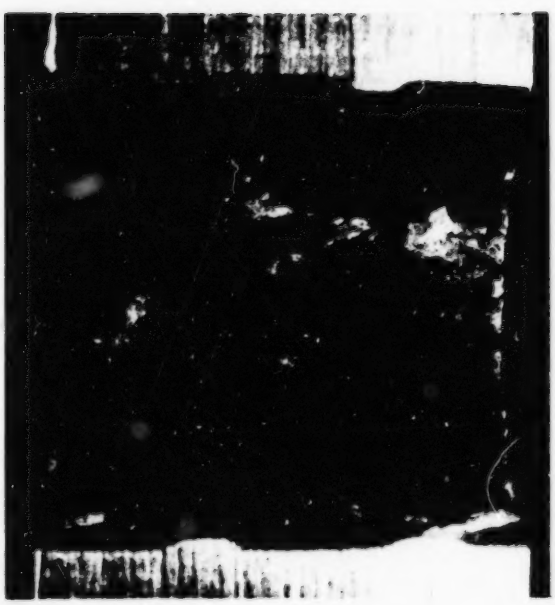


FIGURE 2(a) - HOT SIDE ID SURFACE

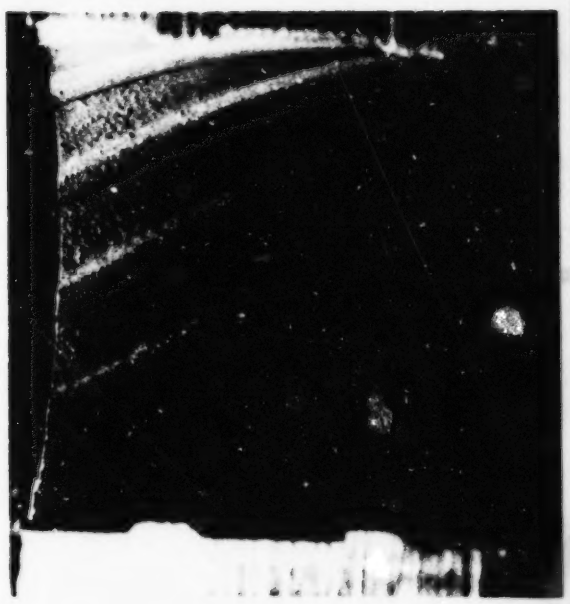


FIGURE 2(b) - COLD SIDE ID SURFACE

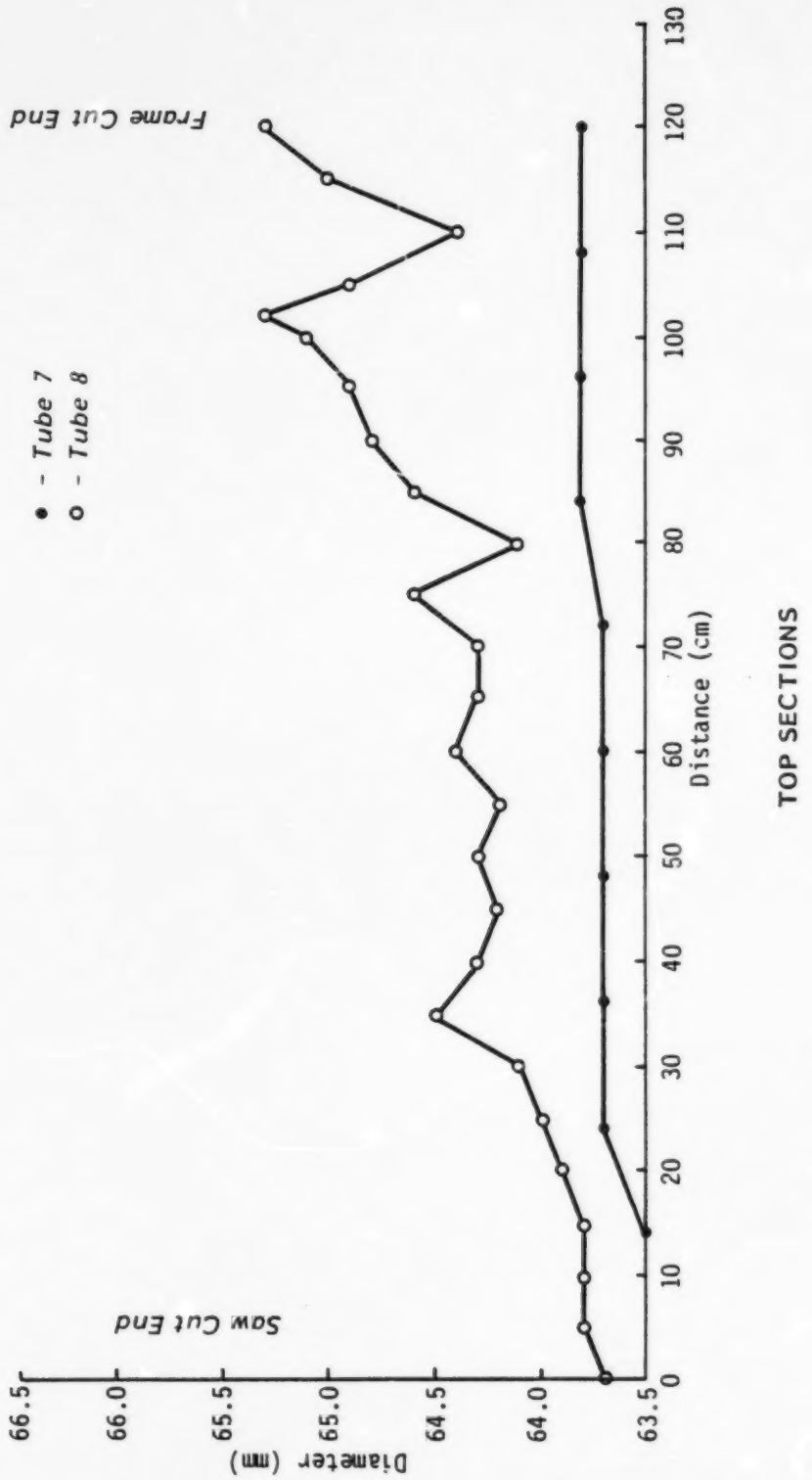


FIGURE 3 - DIAMETRAL MEASUREMENTS - TOP SECTIONS

166944 RD

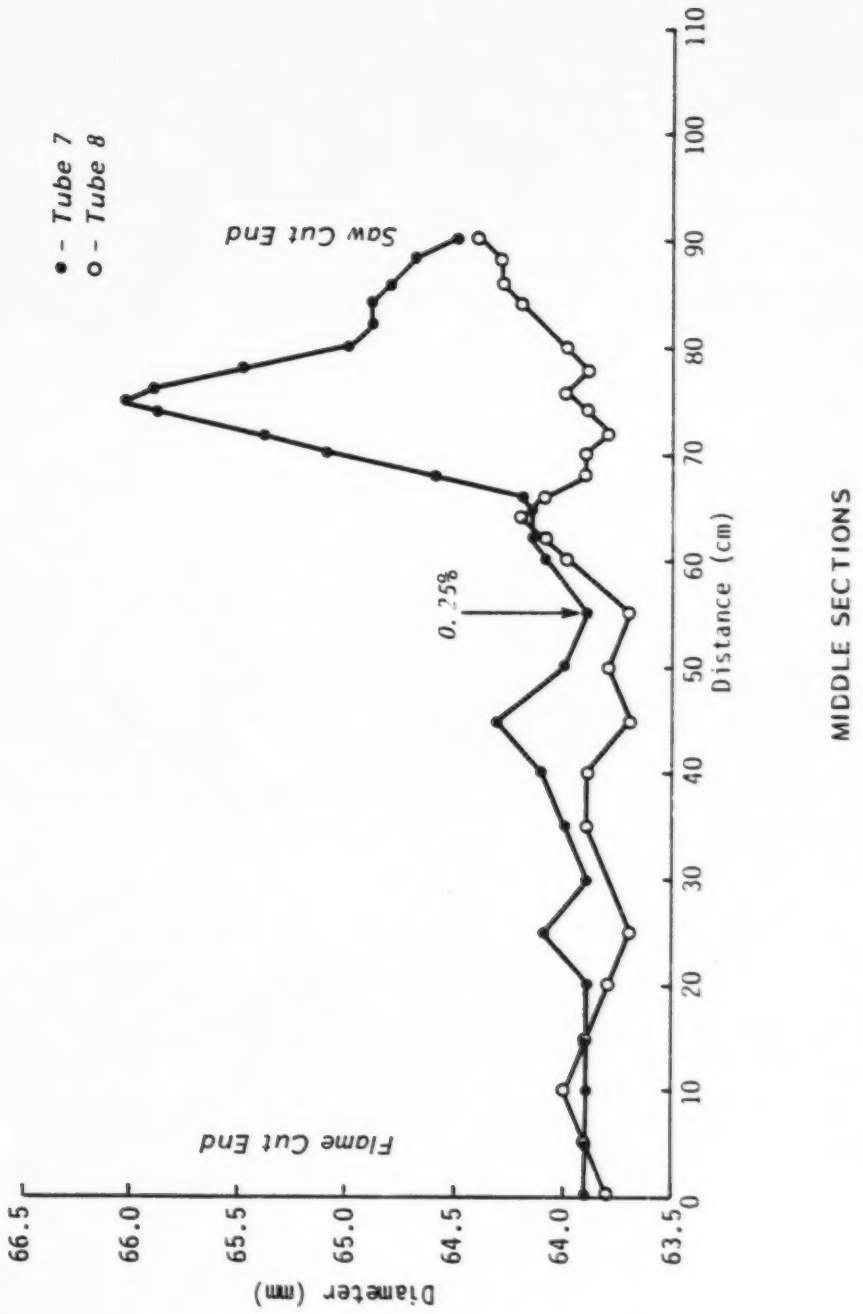


FIGURE 4 - DIAMETRAL MEASUREMENTS - MIDDLE SECTIONS

166943 RD

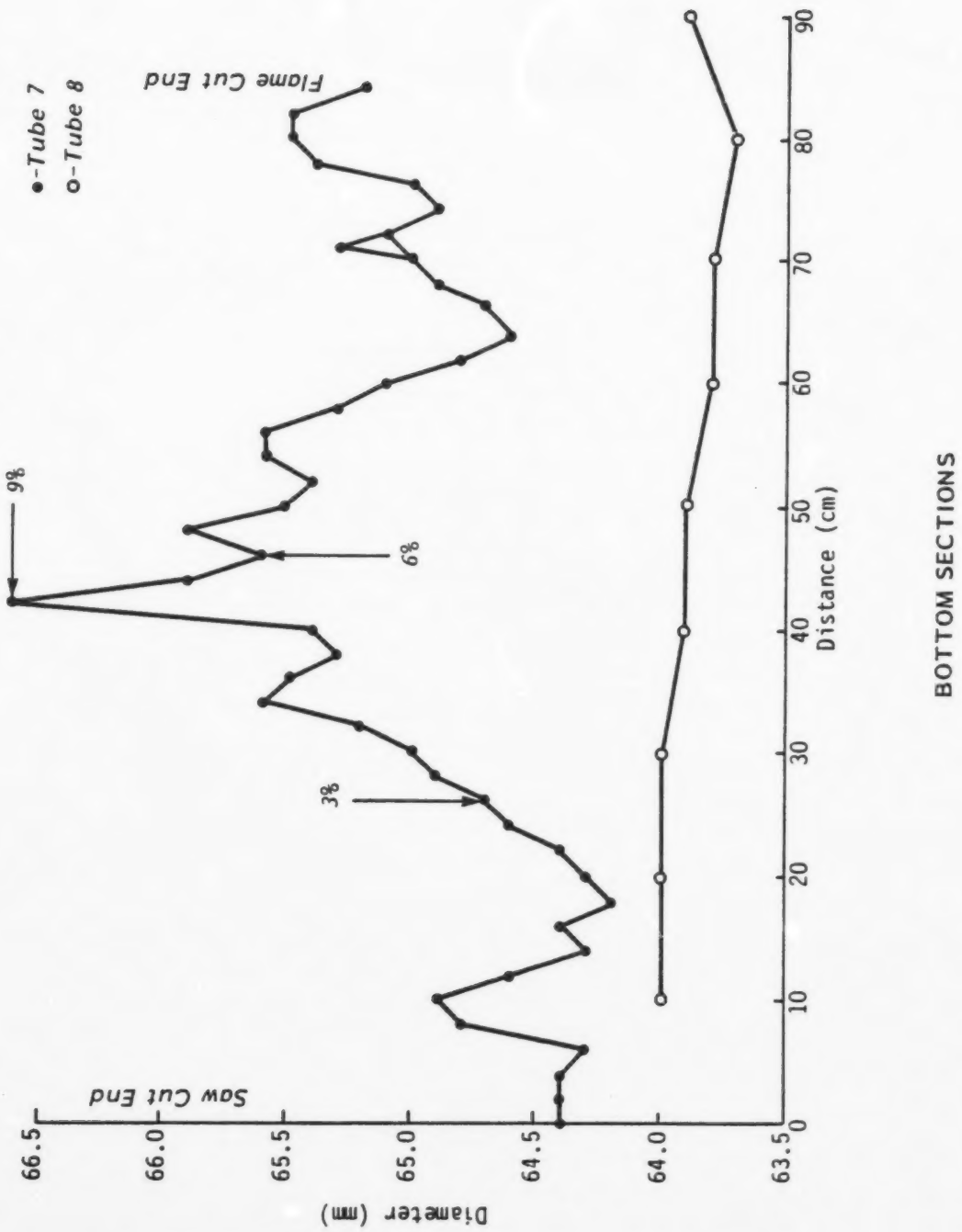


FIGURE 5 - DIAMETRAL MEASUREMENTS - BOTTOM SECTIONS

166945 RD

84-366

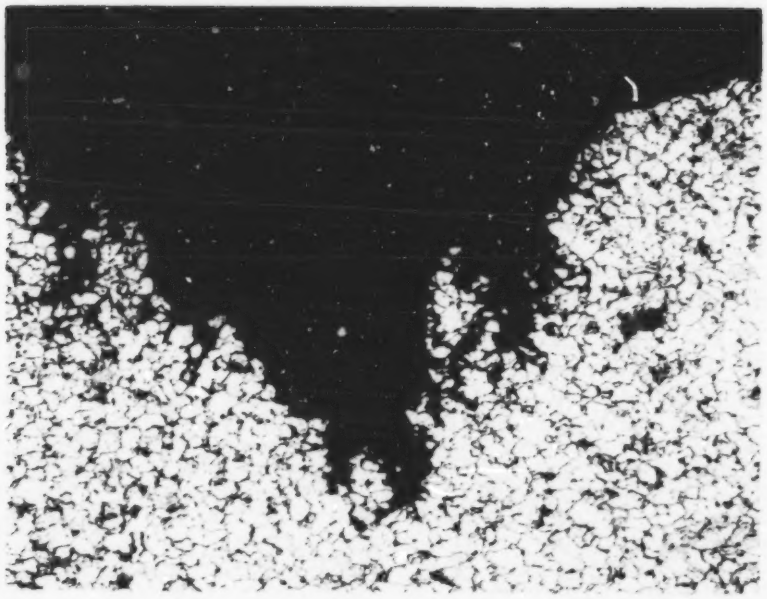


FIGURE 6 - SURFACE DAMAGE - 9% CREEP STRAIN. 200X

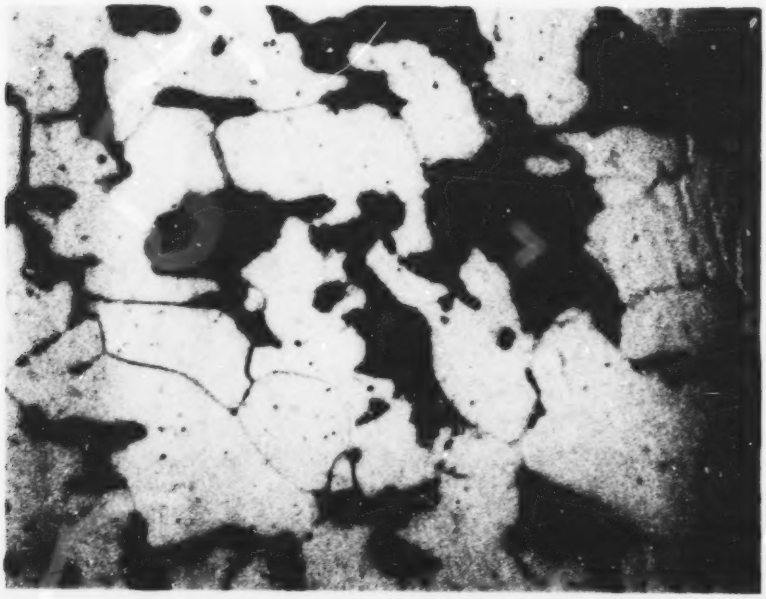


FIGURE 7 - MICROSTRUCTURE FROM TUBE 7, COLD SIDE, AWAY FROM DAMAGE ZONE. 1000X

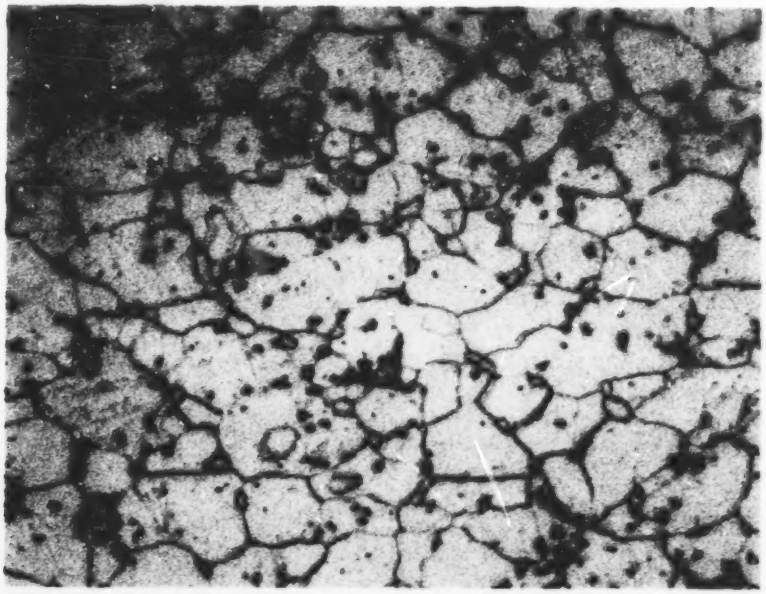


FIGURE 8 - MICROSTRUCTURE AT 9% CREEP STRAIN - HOT SIDE CROWN. 1000X

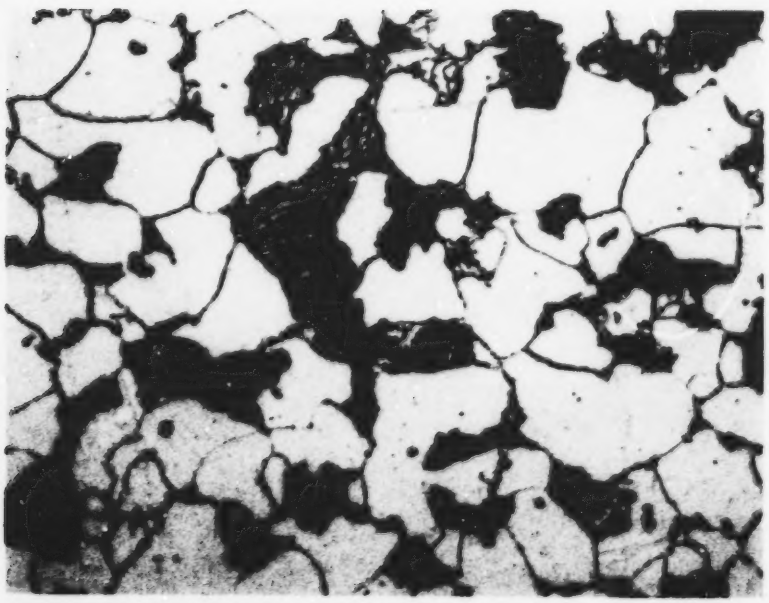


FIGURE 9 - MICROSTRUCTURE 10 mm FROM 8 ABOVE. 1000X

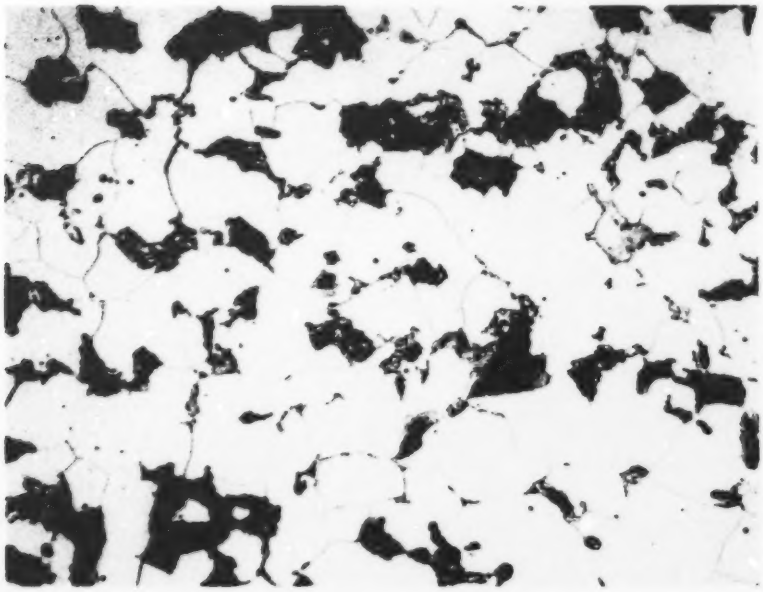


FIGURE 10 - MICROSTRUCTURE AT COLD SIDE - SAME SECTION AS 8 AND 9. 1000X

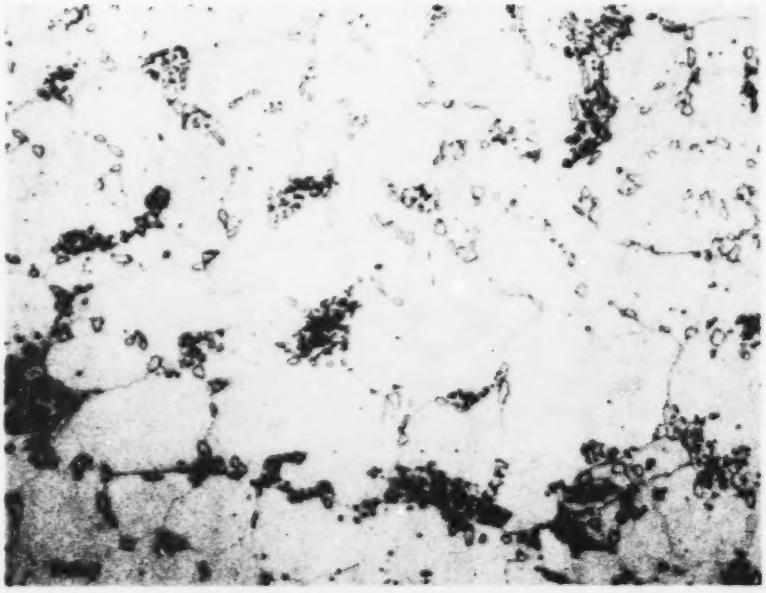


FIGURE 11 - MICROSTRUCTURE AT 6% CREEP STRAIN. 1000X

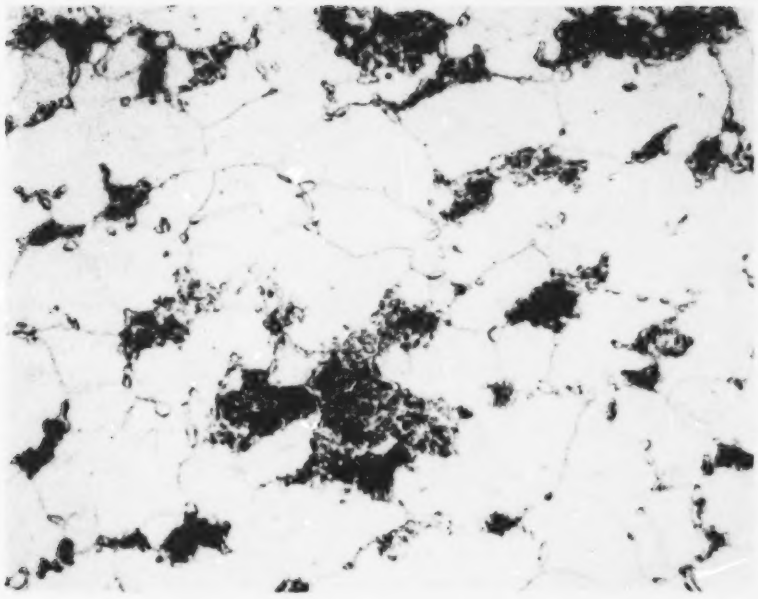


FIGURE 12 - MICROSTRUCTURE AT 3% CREEP STRAIN. 1000X

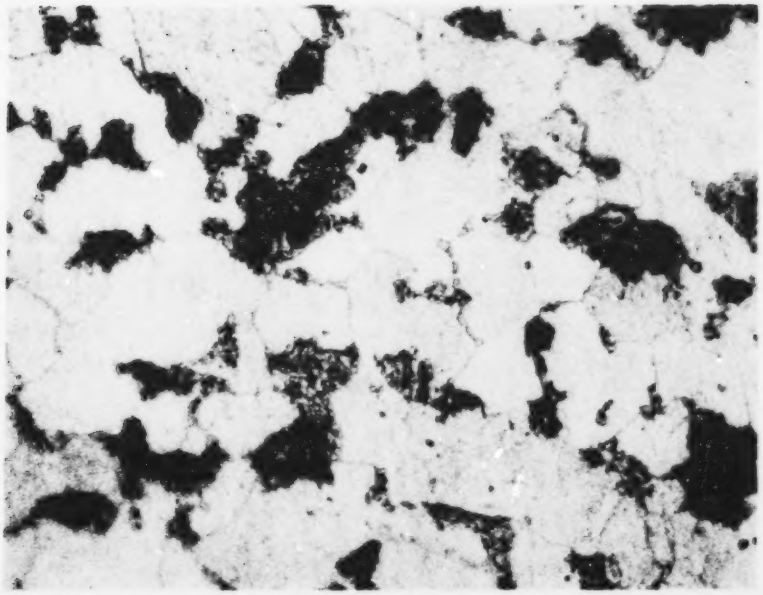


FIGURE 13 - MICROSTRUCTURE AT 0.25% CREEP STRAIN. 1000X

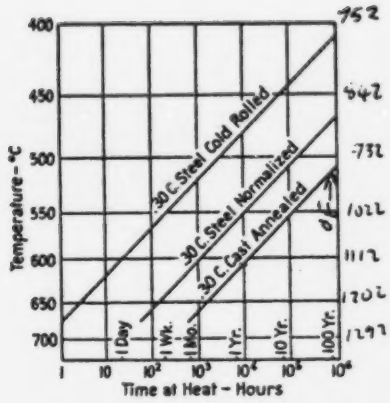
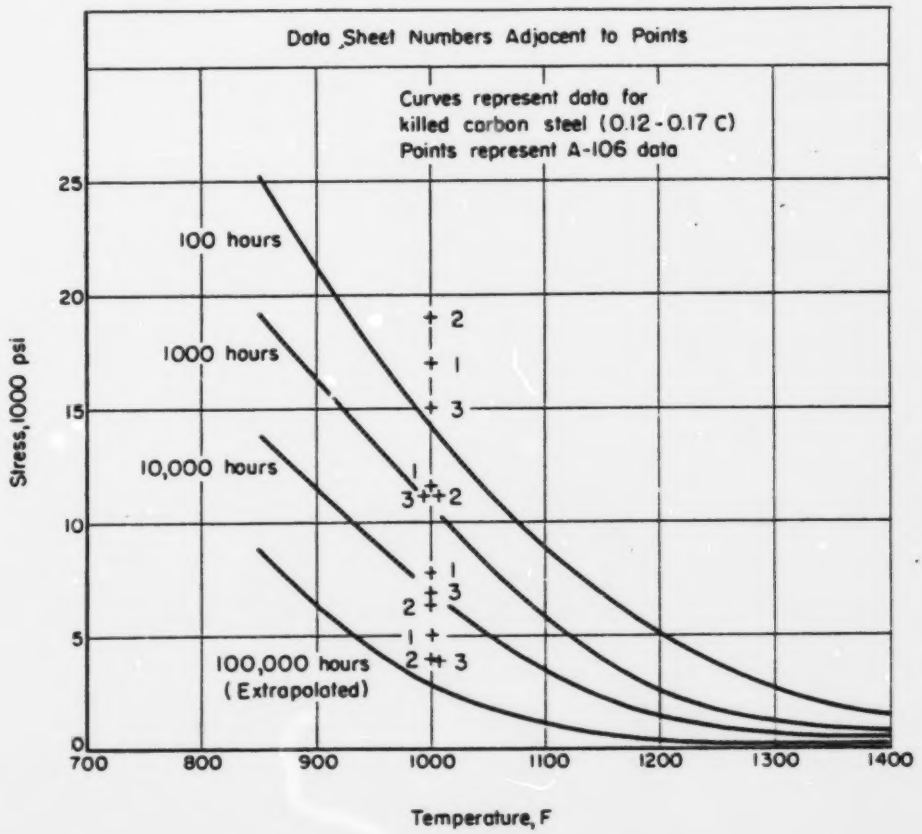


FIGURE 14 - TIME-TEMPERATURE RELATIONSHIPS FOR SPHEROIDIZATION IN CARBON STEEL (REFERENCE 4).



RUPTURE STRENGTH DATA

ASTM A-106, GRADE B PIPE STEEL (0.30 C MAX.)

FIGURE 15 - CREEP RUPTURE DATA FOR CARBON STEEL (REFERENCE 5).